



Research paper

Groundwater as a social-ecological system: A framework for managing groundwater in Pacific Small Island Developing States



Louis Bouchet*, Martin C. Thoms, Melissa Parsons

Riverine Landscapes Research Laboratory, University of New England, Armidale, NSW, 2351, Australia

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ABSTRACT

Groundwater in Pacific Small Island Developing States is a critical source of freshwater for island ecosystems and human communities. Groundwater systems face challenges from growing populations, climate change and climate variability. Many groundwater systems in the region have been inappropriately managed, with increasing occurrences of groundwater pollution and saltwater intrusion. This limits the availability of freshwater, increases the likelihood of contracting water borne diseases, and the cost of access to alternative freshwater sources. In this paper, we argue that groundwater systems are social-ecological systems, where anthropogenic activities and groundwater conditions are linked through dynamic, non-linear processes. We also argue that groundwater management failures in the region, are associated with traditional command and control approaches to management, which ignore the systemic nature of coupled social and ecological groundwater systems; and assumes that groundwater resources, and the dependant human communities can be managed independently. Recognising the linkages and feedbacks between groundwater and dependant social communities is important for the long-term sustainability of groundwater in these regions. Conceptual frameworks are useful tools to order phenomena and material, revealing patterns and processes, and enabling the joining of multiple areas of understanding into a single conceptual-empirical structure. We propose a framework to manage groundwater as a social-ecological system. The framework is comprised of three building blocks: complex adaptive systems, resilience thinking and strategic adaptive management. We discuss how the application of the framework in the Republic of Nauru may alter decades of groundwater mismanagement and steer the resource towards a sustainable path.

1. Introduction

Groundwater is a major freshwater resource, providing drinking water to half of the world's population (FAO, 2016). In the Pacific Region (Fig. 1), groundwater is the only reliable source of freshwater for communities of small atoll islands (IGRAC, 2016). Groundwater resources in Pacific Small Island Developing States (PSIDS) are threatened by many anthropogenic activities. Pollution of groundwater originates from: chemicals derived from agricultural practices; solid waste disposal and industrial discharge; biological pollution from solid waste disposal and sanitation systems; and, hydrocarbon leaks and spills (Dillon, 1997; IGRAC, 2016). The threat of groundwater contamination is high on several islands such as Nauru (Bouchet et al., 2014), Tarawa (Lal, 2014), Kiribati (Metutera et al., 2002), Funafuti and Majuro (IGRAC, 2017a) where groundwater has been deemed unsafe to drink without prior treatment. Proximity to the sea and the overuse of groundwater also increases the threat of saltwater intrusion. In the

Pacific Region, this phenomena has long been observed (Ohrt, 1947; Momii et al., 2005) and is exacerbated by sea-level rise (Berthe et al., 2014; Ketabchi et al., 2016). Many Pacific islands have seen an increase in saltwater intrusion from 2000 to 2010 (IGRAC, 2017a) and a recent sea-level rise impact study showed that saltwater intrusion into groundwater systems is likely to trigger relocation of communities long before the sea submerges coastal areas and islands (Storlazzi et al., 2018). Thus, the groundwater systems of PSIDS are an important, but highly vulnerable, resource for Pacific Island communities.

Given the importance of groundwater for PSIDS, sustainable management of the resource is critical. Many PSIDS have very limited governance structures for the management of groundwater, or to monitor and assess management activities that protect groundwater resources from anthropogenic activities (IGRAC, 2016). A common argument to explain the lack of protection for groundwater resources is that many PSIDS have limited financial, technical and human capacity to do so (Duncan, 2011; Moglia et al., 2008; UNESCO-IHP, 2015; White

* Corresponding author.

E-mail address: lbouche2@myune.edu.au (L. Bouchet).<https://doi.org/10.1016/j.gsd.2019.02.008>

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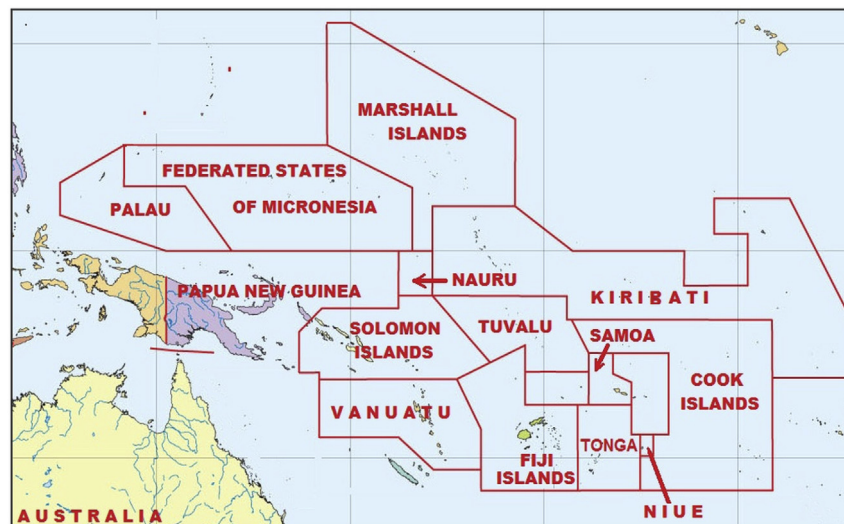


Fig. 1. Pacific small island developing states. After Dornan (2015).

and Falkland, 2010). However, this cannot be the sole justification for management lapses because there is ongoing commitment of donors to financial and technical assistance in the region. An estimated AUD\$1.7 billion was available for groundwater management activities in 2016¹ (OECD, 2018). The limited progress toward sustainable groundwater management in PSIDS may be linked to traditional command and control management approaches that pervade groundwater management. Command and control is a type of management characterised by centralised top-down control and technocratic approaches (Cox, 2016; Holling and Meffe, 1996), where the resource and community expectations are managed separately. The management approach to groundwater in PSIDS is symptomatic of the command and control approach. There is a central authority responsible for groundwater management but it has limited in-house technical personnel. The authority is thus strongly tied to regional agencies and donors who offer technical assistance through consulting experts (Bouchet et al., 2014). Experts may have professional motivations in proposing certain interventions over others. Technical fixes (institutional and technological) are often led by consulting experts, through short term donor projects (Clarke et al., 2014). Solutions are often based on the replication of measures efficient in other groundwater systems or on the assumption that groundwater systems are generally simple to conceptualise, with clear boundaries and linear cause to effect relationships. The community may be involved in donor projects, but participation is often limited by the short time-frame of most donor projects (Clarke et al., 2014).

Command and control approaches to the management of groundwater resources in PSIDS - technical solutions - are often not well-fitted to the local context. For example, the development of national water policies to regulate water sectors, including the protection of groundwater resources, did not obtain social consensus over groundwater ownership and has led to inaction in many PSIDS (Bouchet et al., 2014). Subsequently, most PSIDS have limited, if any, legislation in place to manage groundwater resources and regulations that do exist are often poorly enforced (Bouchet et al., 2014). Solutions also do not address the root causes of issues and instead treat the symptoms. For example, many short-term donor projects seek to improve infrastructures through small-scale projects without sufficient time commitment and community leadership to ensure a lasting acceptance. This leads to rejection and non-sustainable investments (Clarke et al., 2014), perpetuating

inadequate management practices and further system degradation. In 2016, after decades of donor support for the water sector in the region, many PSIDS have failed to make sustainable progress toward regional and international goals (Belmar et al., 2016) or the establishment of groundwater monitoring (IGRAC, 2016).

Groundwater systems in PSIDS are social-ecological systems (SES) in which human communities, aquifers and dependant ecosystems are linked. Groundwater in PSIDS provides a range of ecosystem services including the supply of freshwater and the support of groundwater dependant ecosystems (Keener et al., 2012; Johannes, 1980). Anthropogenic activities effect groundwater aquifers through extraction, land use and pollution, which in turn influence natural recharge processes and groundwater quality. Aquifers, Groundwater Dependant Ecosystems (GDEs) and human communities interact through dynamic, non-linear relationships and open boundaries (Comte et al., 2015; Pokhrel et al., 2015). These interactions contribute to a dynamic SES, where change in one system component (e.g. groundwater extraction rate) does not necessarily lead to a change of similar magnitude in a connected component (e.g. saltwater intrusion). The openness of the groundwater SES allows driving forces at multiple scales (e.g. rainfall, climate, global economy, extraction rates) to influence groundwater systems. Within the groundwater system, human communities have the greatest influence on groundwater quality and availability. In PSIDS, human interaction with the resource is governed by formal and informal mechanisms at many levels (i.e. dwelling, community, island, state and international levels). Consequently, the social and ecological components of groundwater as a SES cannot be studied in isolation. Rather, understanding groundwater as a SES requires holistic approaches that use principles of sustainability and which view humans as part of the groundwater system, not as external drivers to the system (Thoms et al., 2018).

Socio-hydrology has been proposed as an approach to identify and predict the dynamic features of coupled human-water systems (Sivapalan et al., 2012). Socio-hydrogeology has developed alongside socio-hydrology, and emphasises the importance of knowledge exchange, networked stakeholder engagement, interdisciplinarity and effective communication in sustainable groundwater management (Re, 2015; Hynds et al., 2018). Socio-hydrogeology situates hydrogeologists as facilitators of knowledge exchange, proposing that hydrogeologists are 'leaders via advocacy, mediation, translation, and promotion of best practice; they are in a unique position to advocate for appropriate groundwater management and protection, promote and develop experience at the local/catchment scale into regional or national management strategy, and assist in translating between the ideal (science)

¹ Total net receipt from Official Development Assistance (ODA) to Oceania countries.

and the achievable (practise)' (Hynds et al., 2018: p.10). Resilience thinking is an alternative perspective to the conceptualisation of human-groundwater interactions. Resilience thinking proposes that humans are embedded within ecosystems, and feedbacks within a SES generate system dynamics at multiple scales (Folke et al., 2010). Resilience thinking assumes that SES behave as complex adaptive systems, with the capacity to learn and adapt to changing conditions that may occur gradually or in response to a shock (Folke et al., 2010). Resilience is the capacity of the SES to absorb shocks and to persist to sustain ecosystem services and human well-being (Walker et al., 2004). While socio-hydrogeology and resilience thinking both stress the importance of stakeholder engagement in resource management, this paper explores the sustainable management of groundwater using a framework situated in resilience thinking. Specifically, it explores groundwater as a social-ecological system and develops a framework for managing groundwater using the tenets of resilience thinking including complex adaptive systems, resilience, thresholds and adaptive co-management.

There is a disconnect between the value of groundwater and the management of groundwater in PSIDS. While there is a need to better integrate social and ecological systems for sustainable use of groundwater, the resilience-related concept of SES has not been applied to groundwater systems. Conceptual frameworks are useful tools to detail new research approaches as they provide a logical structure to assist the integration of various disciplines and associated concepts. Conceptual frameworks are commonly used in interdisciplinary research (DeLong and Thoms, 2016; Dollar et al., 2007). They are useful tools for integrating different disciplines and are used widely as a means to organise ideas, understand systems, link cause and effect, and guide decisions about system management (Parsons et al., 2009). A framework for managing groundwater as a social-ecological system in PSIDS is developed in this manuscript. The framework is centred on three building blocks:

1. A complex adaptive systems approach to viewing groundwater: What are the characteristics of a groundwater system as an SES?
2. Sustainability and resilience thinking: Why is considering groundwater systems as SES necessary to sustainably manage the resource?
3. Strategic Adaptive Management: How can a groundwater SES be managed to improve and/or retain its sustainability?

2. Framework components

The framework for groundwater as an SES is organised using three building blocks: complex adaptive systems, resilience thinking and

Strategic Adaptive Management (Fig. 2). The first building block addresses the characteristics of groundwater systems from a social-ecological perspective. Systems thinking is used as the overarching scientific premise because it allows an understanding of the properties that explain the behaviour of groundwater as a complex adaptive system. The second building block addresses the sustainability of groundwater. Resilience thinking is used as a philosophical lens to understand the dynamics of complex systems that allow them to absorb disturbances, maintain function and persist, which is a prerequisite for sustainability (Fazey, 2010; Walker et al., 2004; Walker and Salt, 2006). The third building block addresses the management of groundwater as a SES. Strategic Adaptive Management (SAM) is used because it allows the management of groundwater as a SES. Using principles of resilience and systems thinking, SAM provides an approach to groundwater management that focuses on learning, adaptation and experimentation. This is important in contexts where knowledge of the resource is limited and conflict over the management of the resource is high (Roux and Foxcroft, 2011; Williams and Brown, 2016).

2.1. Complex adaptive systems

2.1.1. Properties of complex adaptive systems

A complex adaptive system (CAS) is one that involves many interacting components that adapt or learn as they interact (Holland, 2006). The dynamic and adaptive nature of a CAS is of central importance and the study of CAS generally focuses on how systems change their structure and function in response to external or internal pressure and interactions between system components (Chan, 2001). The dynamics of CAS is governed by fundamental properties including self-organisation; long- and short-term interactions; non-linear dynamics and feedbacks; path dependency; openness; and, emergence (Cilliers and Spurrett, 1999). Three of these properties are of major importance to the framework for managing groundwater as a SES: self-organisation; non-linear dynamics and feedbacks; and, system openness.

Self-organisation refers to the ability of complex systems to create a form of order where components interact following tacit rules without the presence of a central or external control (Mahmud, 2009). Complex adaptive systems are adaptive because they have the capacity to re-organise themselves at critical points of instability, to absorb disturbances and return to a stable state (Levin, 1998). A stable state is thus created by a CAS through self-organisation. System functions also depend on self-organisation and, under pressure, a system might lose, gain or change function to accommodate new persistent conditions. Complex adaptive systems are generally sensitive to a small subset of

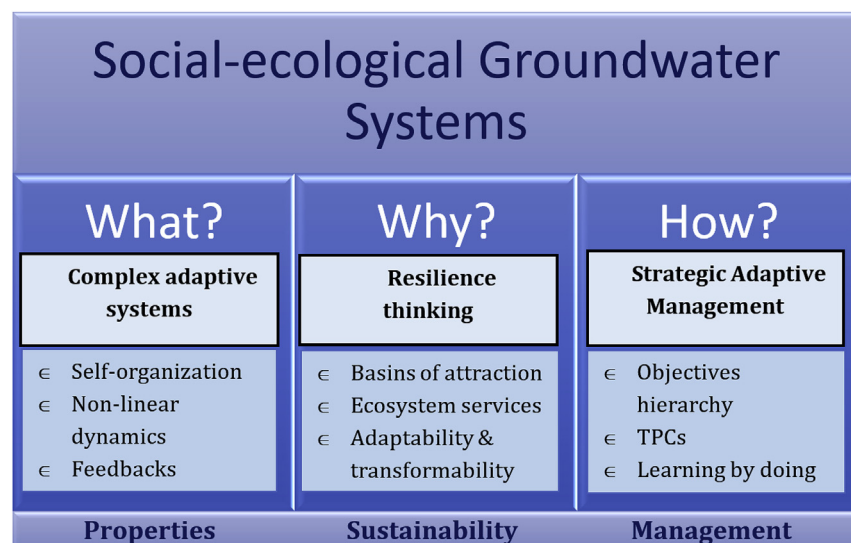


Fig. 2. Framework for managing groundwater as a social-ecological system. The framework is organised into three building blocks: complex adaptive systems, resilience thinking and Strategic Adaptive Management. Each block addresses a key question for sustainable groundwater management: What are the properties of a groundwater system as an SES; Why is considering groundwater systems as SES necessary to sustainably manage the resource; and, How can a groundwater SES be managed to improve and/or retain its sustainability?

variables, whose changes can trigger system re-organisation (Anderson, 1999).

The self-organisation of CAS occurs through mechanisms of non-linear dynamics and feedbacks. Because of non-linear dynamics, a change in one system variable does not always produce an outcome that is proportional to that change (Rickles et al., 2007). Thus, CAS cannot be studied as the combination of their individual parts, and CAS also have limited predictability (Cilliers and Spurrett, 1999). Feedback mechanisms explain the non-linear dynamics through which CAS self-organise. A part of a system receives feedback when the way its neighbours interact with it at a later time depends on how it interacts with them at an earlier time (Ladyman et al., 2013). Feedbacks are of two main types: reinforcing (positive) and balancing (negative). Balancing feedbacks are an important tacit rule within CAS that help maintain the system in a stable domain (Mittleton-Kelly, 2003). Conversely, reinforcing feedbacks can lead to drastic change in the system and re-organisation until a new stable state is reached, with a set of balancing feedbacks.

Openness refers to the degree of connectivity of a system with other systems at larger scales. As open systems, CAS are defined at various temporal, spatial and organisational scales (Redman et al., 2004). To study a complex system, spatial, temporal and organisational boundaries must be set to acknowledge exogenous components and processes that are outside the defined system but which may influence the flows of materials and information into and out of the system (Walker et al., 2012). These drivers set conditions for internal variables, influencing system processes (Virapongse et al., 2016; Walker et al., 2012). Unlike components within the system, drivers are not affected by variables within the system.

2.1.2. Groundwater systems as complex adaptive systems

Groundwater systems have characteristics reflective of complex adaptive systems. They are dynamic and adaptive systems that comprise of 3 sub CAS: The aquifer, the natural environment which include GDEs and the island communities that lives above aquifers (Fig. 3). The main function of the groundwater system is the delivery of ecosystem services such as the storage and provision of freshwater; the sustaining of GDEs, also vital to local communities; and the mitigation of droughts (Griebler and Avramov, 2014). The groundwater system may change its structure (i.e. the nature of the interactions within the system) which may affect its function under pressure from within the system or from human or environmental drivers.

In groundwater systems, self-organisation can occur within each of the three subsystems and effect the system as whole. For example, in the island natural environment, spatial self-organisation can be observed from vegetation exposed to climate disturbances. Under

sufficient disturbance, vegetation may reorganise spatially to best thrive with changing conditions (Vincenot et al., 2016). The change in vegetation distribution may affect the island communities, who rely on its abundance for uses such as food, medicine and building material; and the aquifer, when water balance is affected by the change in evapotranspiration. Within the island community, self-organisation may refer to the ability of local communities to organise the management of shared groundwater resources without any formal control by state and local institutions. Self-organisation and self-regulation of groundwater resources is prevalent in the PSIDS as groundwater resources are mostly privately owned, traditionally attached to land titles (White and Falkland, 2011). Self-organisation is often triggered as a response to disturbances that affect system function. For example, in 1998 on Majuro Atoll, an increase in groundwater abstraction from public utilities led to saltwater intrusion in the island's aquifer. The increase in salinity was of concern to the local community that lives above the aquifer and relied almost exclusively on it for their water needs. In response to concerns over long-term damage to the aquifer and loss of ecosystem services for their community, they requested the government stop pumping water from the aquifer; which they obliged (Bouchet, 2014). Self-organisation is a lever that helped the community absorb disturbance and return to a stable state without losing system function. This example also illustrates how a change in only one variable (i.e. aquifer salinity) can affect an entire system.

Self-organisation of groundwater systems is led by nonlinear dynamics and feedback mechanisms. Self-organisation of vegetation, for example, may be due to a balancing feedback mechanism with seawater intrusion. This feedback was observed by Comte et al. (2015) in a small coral atoll and revealed that an increase in seawater intrusion causes a decrease in vegetation, because many species cannot survive in highly saline conditions. The decrease in vegetation then facilitates an increase in aquifer recharge, which reduces aquifer salinity. Self-organisation of human communities may be triggered by a reinforcing feedback between seawater intrusion and pumping. This feedback is widely acknowledged (e.g. Sherif and Singh, 2002; Kura et al., 2014) and was observed by Paniconi et al. (2001) in the coastal aquifer of Eastern Cap-Bon, Tunisia where, under certain pumping conditions, seawater intrusion occurs at a faster rate than it takes for the groundwater table to drop and release water. The more seawater that is drawn to the well, the less freshwater can enter the well, increasing seawater intrusion. This feedback, which creates a steady increase in salinity, forces human communities to reduce or stop pumping to keep groundwater salinity within an acceptable range that maximises its use. The presence of these feedbacks shows the importance of nonlinear dynamics and feedbacks between groundwater, GDEs and human activities. Groundwater systems cannot be studied as the combination of their subsystems

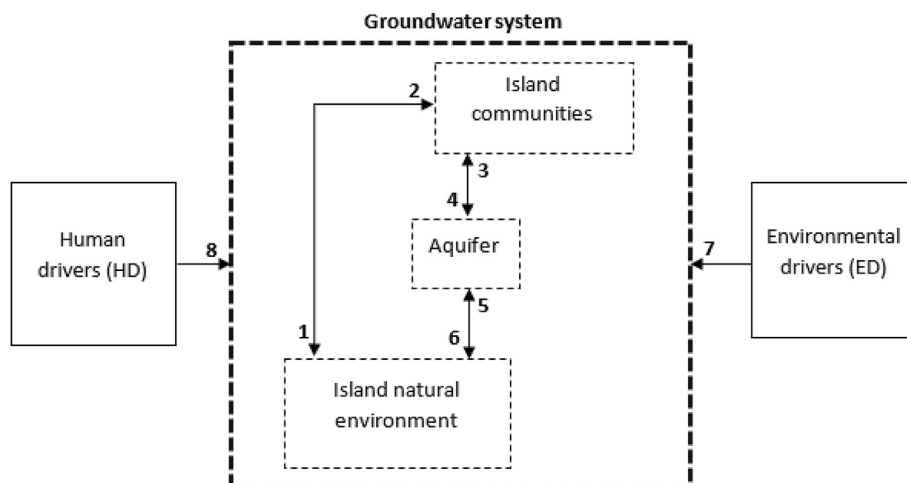


Fig. 3. Groundwater as a complex adaptive system. The main system processes are (1) land use; (2) ecosystem services from GDE; (3) groundwater abstraction; (4) leakages and artificial recharge; (5) Recharge from infiltration; (6) Evapotranspiration from GDE; (7) Rainfall, temperature, sea level; (8) Human drivers including political stability and Gross Domestic Product.

because it would ignore these important feedbacks.

Openness and scale are important properties of groundwater systems. The groundwater system should not be bounded at the aquifer level because social and ecological parameters extend well beyond the aquifer physical boundaries. These social and ecological parameters and processes, connected at various scales, can have important impacts on the fluxes of materials into and out of the groundwater system (Re, 2015; Tringali et al., 2017; Hynds et al., 2018). When identifying the appropriate scale to study the system it is crucial to include components that affect and are affected by the groundwater and to acknowledge that human communities interact in a dynamic, nonlinear, two-way relationship with the groundwater system. Drivers in PSIDS groundwater systems are exogenous forces such as rainfall and sea level and may include human forces at higher scales such as political instability, and Gross Domestic Product (Fig. 3). Thus, the openness of groundwater systems is defined by the processes and feedbacks in the system, particularly between communities and the groundwater resource.

2.2. Resilience thinking

2.2.1. Properties of resilience thinking

Resilience thinking offers a framework to study the dynamics of complex systems in the face of change. Originating in the field of ecological science in the 1970s, resilience thinking has evolved to a transdisciplinary science with wide application. Ecological resilience was first defined by Holling (1973) as “the amount of disturbance that an ecosystem can withstand without changing self-organized processes and structures”. Ecological resilience considers ecosystems as complex systems with multiple stable states. Studying ecological resilience thus focuses on maintaining existence of function in ecological systems (Schulze, 1996). Four components of resilience thinking are of relevance to PSIDS groundwater systems: basins of attraction and tipping points; ecosystem services and the potential loss that might occur between two stable states; the adaptability and transformability of the system; and, the prerequisite of resilience for sustainability.

Understanding the disturbance that a system can absorb before it reaches a tipping point and moves into a new basin of attraction is the main objective of resilience studies (Carpenter et al., 2001). A complex system is constantly changing (i.e. the variables characterising its structure and function are changing) but the structure of the system (i.e. key variables and processes that support function) tend to remain within the same basin of attraction (Fig. 4), supported by balancing feedbacks (Walker et al., 2004). Complex systems are generally controlled by a small number (4–6) of variables (Walker et al., 2012). These key variables are also called slow variables because they tend to change slowly over time (Walker et al., 2012). A disturbance of sufficient magnitude may push the system across a tipping point into a new basin of attraction, in which the system no longer has the same structure, function and feedbacks (Fig. 4). One area of resilience thinking

called specified resilience, focuses on identifying tipping points for slow variables (Carpenter et al., 2001). Understanding for which value (or range of value) in its slow variables a system is likely to move into a new basin of attraction allows human communities to better safeguard the provision of ecosystem services by a SES.

Ecosystem services represent the services that human communities receive from their natural environment (Daily et al., 1997). Slow variables in coupled social-ecological systems are often associated with the delivery of ecosystem services. Although the type and level of services are inherently limited by the natural setting and resources that make up the ecosystem, the desired level of service and the value that society places on an ecosystem is subjective. Therefore, tipping points for slow variables in social-ecological systems may be subjective and hard to define (Carpenter et al., 2001). Resilient systems are able to self-organise in the face of disturbance, to maintain a sufficient level of ecosystem services and thus avoid crossing a tipping point into a new basin of attraction. Identifying tipping points is challenging but can provide great insight into a system behaviour and delineate operational boundaries. Tipping points exist when two relatively close values for a slow variable lead to two different system states, with distinctively different function and ecosystem services (i.e. State 1 and State 4, Fig. 4.). System states are of limited reversibility and exhibit significant self-organisation noticeable through new balancing feedbacks (Milkoreit et al., 2018). Thus, ecosystem services on each side of a tipping point must show lasting differences, characteristic of different basin of attraction (i.e. intermittent loss in ecosystem services due to disturbance are not necessarily service losses).

Adaptability and transformability are also important elements of resilience thinking because these represent the capacity of human communities to shape variability and change in the state of the system (Folke, 2016). Adaptability is the capacity to maintain or improve the functions of a system in the face of change (Gallopin, 2006), while transformability is the capacity to create a fundamentally new system when the current system cannot be modified to maintain system function (Walker et al., 2004). Transformation can occur autonomously (e.g. natural selection), intentionally (e.g. human intervention) or externally (e.g. forced by drivers outside the system) (O’Connell et al., 2015). Both adaptation and transformation can be seen as levers that humans can use to modify the system’s resilience and avoid undesirable regime shifts (Folke, 2016).

Understanding system dynamics is a necessary condition for sustainability of natural resources (Perrings, 2006). Sustainability can be defined as “the degree to which the system maintains levels of service in the long-term whilst maximising social, economic and environmental goals” (Ward and Butler, 2016). Sustainability of a social-ecological system is thus the ability to maintain ecosystem services for future generations while fulfilling society’s social ambitions. Non-sustainable systems are not always obvious because of the non-linearity that characterises complex systems. A complex system may appear sustainable until

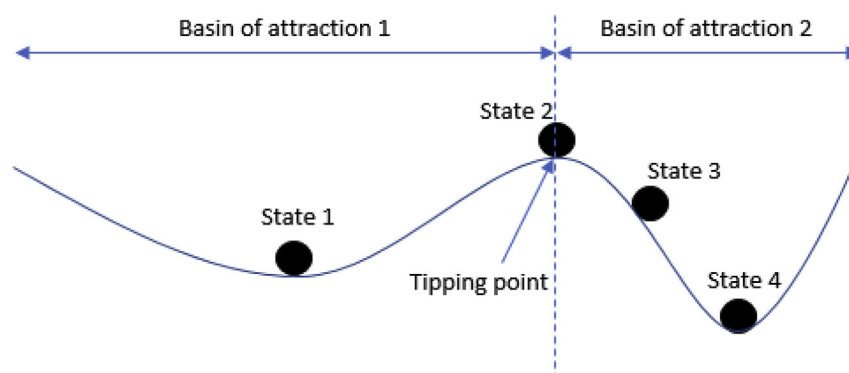


Fig. 4. The basin of attraction, tipping point and system state concepts of resilience thinking. Modified from Bestelmeyer (2015).

sudden and/or unpredicted change occurs and results in the loss of ecosystem services. A prerequisite for sustainability is thus the ability to withstand changes without losing ecosystem services (Derissen et al., 2009).

2.2.2. Resilience thinking and the sustainable management of groundwater

Understanding the disturbance that a groundwater system can absorb before it crosses a tipping point, leading to ecosystem service loss, is important for the sustainability of groundwater systems. Sustaining existing ecosystem services or restoring previous services provided by groundwater systems is a priority in PSIDS as the impact of highly degraded systems, such as found in Nauru and Funafuti, is high for local communities (Bouchet and Sinclair, 2010; Duncan, 2011; Nakada et al., 2012). Degraded groundwater systems pose threats to community health during drought periods when freshwater is limited and groundwater use increases (Sinclair et al., 2012; Emont, 2015). Communities may require replacement technologies (e.g. desalination) that are expensive and complex to maintain and run and which pose additional environmental threats (e.g. brine discharge) that affect the health of GDEs and their ability to provide food to local communities (Younos, 2005). To sustain or restore ecosystem services requires an understanding of system resilience and how change in slow variables will push the system from one regime to another (Folke, 2016).

Groundwater systems in the PSIDS provide many ecosystem services. Freshwater lenses provide island communities with drinking water (Table 1a). However, the freshwater lens might be inconsistent and groundwater quality highly variable, from fresh to brackish (Table 1b). In this state, water can be used for most activities except drinking water. When groundwater quality is very low, it has high salinity and is also likely to be highly polluted (Table 1c). In this state it is mainly used for flushing toilets. Highly contaminated groundwater prohibits all use (Table 1d). As complex system, each state in a groundwater system is maintained by key hydrogeological, social and environmental processes. These processes maintain system function by keeping slow variables within an operational range (Table 1). Although each state is characterised by different slow variables, four main categories of slow variables are associated with changes in the provision of ecosystem services under different states: groundwater quantity (e.g.

Table 1

Four principal ecosystem services from groundwater and associated slow variables: Groundwater Quantity (GT); Groundwater Salinity (GS); Groundwater Quality and Land Use (GLU); and, Groundwater Demand (GD). Percent of daily water need met by groundwater for each type of ecosystem service and groundwater demand is based on the study conducted in Nauru by Bouchet and Sinclair (2010). Electrical Conductivity (EC) limits are based on WHO (2017) and observation in water uses for various groundwater quality by Bouchet and Sinclair (2010).

Ecosystem services	Groundwater states and slow variables
A. Drinking water Provides user with 100% of daily water needs	<ul style="list-style-type: none"> ● GT: Freshwater lens volume > 0 ● GS: EC < 1000 us/cm ● GLU: General pollution is low ● GD: 100% water demand
B. Secondary water (many use but drinking) Provides user with up to 90% of their daily water needs	<ul style="list-style-type: none"> ● GT: Freshwater lens volume inconsistent ● GS: EC varies but generally < 5000 us/cm ● GLU: General pollution is low to high ● GD: 50–90% water demand
C. Limited use water (i.e. toilet flushing) Provides about 25% of daily water needs	<ul style="list-style-type: none"> ● GT: Freshwater lens volume inconsistent ● GS: EC varies but generally > 10,000 us/cm ● GLU: General pollution is low to high ● GD: 25% water demand
D. Non- useable 0% water provision	<ul style="list-style-type: none"> ● GLU: Harmful contaminants (i.e. hydrocarbon) ● GD: 0% water demand

aquifer volume; aquifer geometry); groundwater salinity; groundwater demand (e.g. percentage of total water use; volume per capita/per day); and, groundwater quality associated with land use (e.g. vegetation type and density; point source pollutants). Maintaining the supply of ecosystem services from groundwater needs to be cognizant of how quantity, quality, salinity and demand variables can push a system into a new basin of attraction.

A shift may occur if a slow variable crosses a tipping point, permanently changing the type of ecosystem services provided by the system (Walker et al., 2004). For example, climate drivers such as repeated droughts or storm surges can increase salinity levels in aquifers (White et al., 2007). If they occur regularly enough, they can change the average salinity (Storlazzi et al., 2018). When a previously fresh aquifer becomes predominantly brackish, it can no longer be a reliable source of freshwater: this illustrates a regime shift (from A to B: Table 1). This regime shift may also occur if the shallow aquifer is significantly disturbed, such as occurred in Funafuti following major land reclamation and borrow pits during the second world war (Duncan, 2011; Nakada et al., 2012). Inversely, an increase in average precipitation of sufficient magnitude can increase groundwater recharge and produce the opposite regime shift. Tipping points are difficult to measure because they are dependent on how human communities and GDEs respond to change (Folke, 2016). Some systems will have greater tolerance to salinity increase. The tipping point for salinity is thus dependant on a social regime shift, where groundwater demand is significantly affected and triggers system re-organisation. A social regime shift occurring without an ecological regime shift may also be sufficient to push the system into a new state. For example, the increasing reliance of a growing population on groundwater can increase aquifer salinity to a point where communities have to re-organise and find additional water sources, at least for drinking. The ecological state change is in theory reversible and maintained only by human pressure. However, when a groundwater resource becomes largely abandoned for drinking, it can trigger reinforcing feedbacks, from behaviours that may increase pollution and further degrade the resource. The further the resource is degraded, the less it can provide services, the less it is valued and the less likely it is for ecosystem services to ever be restored.

The adaptive capacity of groundwater systems can help prevent or facilitate state change. From the social perspective, adaptive capacity refers to the capacity of island communities to self-organise and respond to change in groundwater quality by altering their behaviour. Adaptation can also be driven by institutions through regulatory or technical responses. Adaptive responses may target groundwater use, land use, wastewater disposal and pollution. When adaptation is not feasible, often due to a new ecological regime, transformation might be required from the social system to find another way to access water. In PSIDS this is often through a mix of rainwater and desalination technology (Falkland, 1999; Moglia et al., 2008; White and Falkland, 2012). Adaptation is often a preferred option, since transformation may require the deployment of new technology, such as desalination units, which are expensive and complex to run and maintain (Scholes, 2012).

2.3. Strategic adaptive management

2.3.1. Properties of strategic adaptive management

Adaptive management approaches account for uncertainty in a complex system by trialling management options designed to gain insight about system dynamics and improve its management (Curtin and Parker, 2014). Adaptive management may reveal key feedbacks, self-organisation patterns, openness and tipping points. By increasing knowledge of the system, adaptive management approaches can help increase adaptive capacity and sustainability of complex systems.

Strategic Adaptive Management (SAM) is a form of adaptive management that has been developed and implemented in South African national parks (Roux and Foxcroft, 2011). A notable difference that sets SAM apart from other adaptive management approaches is its strategic

component: it helps foster action and organise management activities, notably through the use of an objectives hierarchy and thresholds of potential concern (Meffe, 2002; Rogers and Biggs, 1999). It also allows the development of flexible structures to integrate various type of knowledge, including cultural, social, technical, and institutional (Rogers et al., 2000). Strategic Adaptive Management is thus a process designed to be adaptive, participatory and strategic (Roux and Foxcroft, 2011) by investigating system desirability, conducting experimental management practices that are aimed at steering the system toward its desired state, and systematically reviewing and learning from management practices. Three components of SAM are of interest for this framework: the objectives hierarchy; TPCs; and, learning by doing.

2.3.2. Components of SAM

The objectives hierarchy within SAM is the mechanism to formulate goals in a hierarchical order and to set measurable targets for system management. The objectives hierarchy enables managers to develop activities for tangible, smaller objectives, while working toward a better understanding and eventually management of the higher order objective (Kingsford and Biggs, 2012). In doing so, it allows managers to initiate management measures when knowledge of the system is limited. The objectives hierarchy is part of the strategic aspect of SAM and, along with social inclusion, it helps foster participatory action and facilitate learning.

Thresholds of Potential Concern (TPCs) are operational targets for monitoring progress toward management objectives (Allen et al., 2011). Because tipping points are dynamic and hard to define in complex SESs, TPCs can be used to monitor slow variables that potentially lead to loss of ecosystem services. TPCs may also be used with other variables known to have a potential leverage on the system. Since thresholds are dynamic and may be desirable or undesirable, they must be reviewed regularly as part of the evaluation and learning process of SAM (Biggs et al., 2011).

Learning by doing is an important tenet of adaptive management approaches and learning is embedded within SAM. Depending on the system boundaries, learning may be mainly about the ecological system (i.e. reducing ecological uncertainty) but may also be about the social system (i.e. what social and institutional structures are the most efficient to sustainably manage the resource). In targeting small experiments to get a better understanding of the system, SAM (and AM approaches in general) offer an alternative to “passive adaptive” and “deferred action management style” (Walters and Hilborn, 1978). In deferred action management, management actions and practices are put on hold in favour of studies. The idea is that the system cannot be managed until it is fully understood. Because of the complexity and dynamic nature of natural resource systems, there might never be sufficient data and the absence of management practices is likely to incur more degradation. In a passive adaptive approach, management practices are developed based on local studies and experiences from similar systems, with the aim to be refined as more studies are conducted. However, in application, practices are rarely reviewed (Walters and Hilborn, 1978). Furthermore, the focus is on a steady state of the system with objectives based on optimistic predictions and a tendency to not question initial assumptions often on the basis of their validity in other contexts (Walters and Hilborn, 1978).

2.3.3. Managing groundwater using strategic adaptive management

A Strategic Adaptive Management approach can help address two key issues for groundwater management in the region that are characteristic of command and control management style: the hegemony of foreign technical experts to design and control the implementation of management activities (Dornan and Pryke, 2017); and the mechanistic approach to groundwater management. First, there is a high reliance on foreign technical experts in the PSIDS, as many countries have limited financial and skilled human resources. Donor agencies and partners fill this gap by providing technical expertise and funding, often through the

implementation of short-term projects. Although expert advice is needed in specific areas such as hydrogeology (White and Falkland, 2011), many aspects of project design and implementation are controlled by technical experts through short term projects (< 5 years). This limits community involvement, necessary for project sustainability (Keppel et al., 2012; Upadhyay, 2005) and hinders behavioural and socio-economical changes which demand longer commitment (Keppel et al., 2012). A post-project review by Clarke et al. (2014) to assess the lasting impact of 27 community development projects for the water and sanitation sector in PSIDS found that only 1 out of 27 projects have had lasting benefit to the targeted communities and could thus be deemed sustainable. Secondly, the mechanistic approach to groundwater management fails to acknowledge groundwater systems as SES and thus to understand the importance of community self-organisation for the management of the resource, the nonlinear dynamic between groundwater, island communities and the natural environment and the openness of the system. It fails to acknowledge that groundwater systems can exist in different stable states, with fundamental differences in their ability to provide ecosystem services to island communities. Consequently, the design of management options is often technical, addresses causes, not roots, of issues and is not well fitted to local contexts. Groundwater systems are also at risk of crossing a tipping point, where groundwater cannot provide the same level of services and communities must rely on expensive, technological solutions, further perpetuating technocratic governance.

The SAM process for groundwater in PSIDS aims to generate long term commitment for groundwater management, where island communities, governments and other stakeholders co-generate management initiatives, based on their knowledge and shared vision. It is a 5-step process that focuses on the improvement of existing management structures and leadership roles (governance) and groundwater management (Fig. 5). Management structures in PSIDS are unique to each setting but share key characteristics such as important informal governance and management structures and ill-defined formal hierarchies of governance (Belmar et al., 2016). Defining the desirable states for the groundwater system is a participatory process that would involve a wide range of stakeholders to develop a vision, objectives and the objectives hierarchy. Safeguarding or increasing ecosystem services might be prioritised as a first order objective, followed by the improvement of management structures and activities. Social inclusion is key in this process to enable consensus over system desirability and derive lower-scale objectives that are realistic, and that drive stakeholders' blended interests. Generating interest from diverse stakeholders at the onset of the initiative is important to foster long term commitment in PSIDS (Keen, 2003; Cvitanovic et al., 2016) and other contexts (Re, 2015; Hynds et al., 2018). For example, integrating donors' research agendas (i.e. research objectives that are interesting to donors) or linking objectives with other sectors is likely important for many stakeholders. An objectives hierarchy supported by a strong social network is also important to avoid setback due to political instability.

Next, TPCs are defined to provide long-term monitoring targets for the slow variables in the groundwater system and additional variables associated with critical system processes. These should include TPCs to measure sustainability, not only of management activities, but of institutional structures, leadership, partnership and engagement. This is key for groundwater sustainability, not only in PSIDS, but for groundwater systems globally. It may also include variables associated with: key characteristics of the social system structure for groundwater management that could reveal a changing behaviour toward groundwater and land use; key characteristics of the GDEs structure and self-organisation patterns; and key biophysical characteristics (e.g. rainfall intensity and frequency). Although qualitative TPCs may be relevant at all levels (e.g. the consumption of groundwater for drinking is purely based on taste, not on TDS measurements), sound scientific data is required to best support management activities (White and Falkland, 2011; Dixon-Jain et al., 2014; IGRAC, 2016). The design and

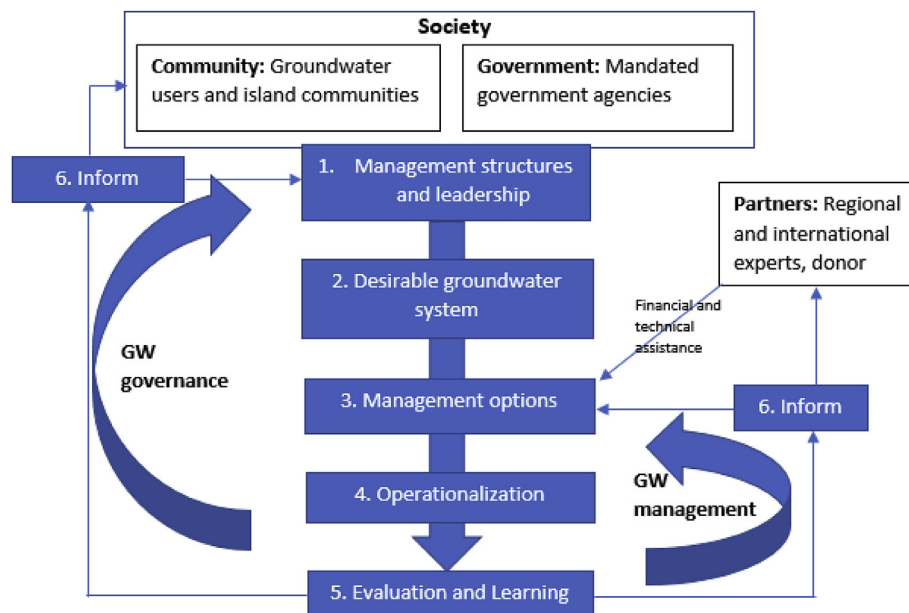


Fig. 5. The SAM process for groundwater systems in PSIDS. Modified from Kingsford and Biggs (2012).

implementation of management experiments will refine TPCs as managers and social structures alike increase the knowledge of the system. As a third step, management options are assessed. Partners might be involved at that stage to provide financial and technical support. Conceptual, analytical and numerical models might be used to predict outcomes and test acceptability. In step 4, management activities are implemented, alongside a monitoring system which uses TPCs as the mechanism to assess the state of the system and its relationship to the goals set in the objectives hierarchy.

The final step is dedicated to learning, through evaluation of management measures and information to stakeholders (McLoughlin and Thoms, 2015). Increasing, co-developing and sharing knowledge within the groundwater SES is key to improve the system's adaptive capacity. The SAM approach for groundwater in PSIDS fosters eco-hydrogeological, technical and institutional learning. Eco-hydrogeological learning is much needed in the PSIDS as uncertainties are high. For example, knowledge of the response of freshwater lenses to sea level rise, seawater movement and environmental pressures is still limited (Dixon-Jain et al., 2014; UNESCO-IHP, 2015; White and Falkland, 2011). White and Falkland (2011) also argues that because groundwater systems in the region are so vulnerable, improving knowledge of these systems is a key to their sustainable management. Technical learning is needed to assess the relevance of technical solutions in various hydrogeological, socio-cultural and economic contexts. Finally, institutional learning provides opportunities to strengthen governance structures and adaptive capacity by understanding and incorporating informal structures, nested leadership and processes that have the power to generate positive changes in the systems.

3. Case study: groundwater as a SES in Nauru

The framework developed in this manuscript provides a road map to manage groundwater as a social-ecological system, using complex adaptive systems, resilience thinking and strategic adaptive management. The framework situates groundwater sustainability as a series of dynamic feedbacks between the social and ecological components of groundwater systems, placing humans as part of the groundwater system rather than external drivers. Management of groundwater systems takes a shared approach with solutions co-generated among multiple societal, scientific and institutional stakeholders, using the structured learning by doing approach of SAM. In this section, we

briefly discuss how the framework could be applied to visualise a SES approach to groundwater sustainability in Nauru, one of the PSIDS. It is not the intent to describe in detail the Nauru SES: rather, we show how the three elements of the framework correspond to groundwater systems in Nauru and how application of the framework elements could potentially enhance groundwater sustainability.

The Pacific Island of Nauru, is a 22 km² independent island nation of 10,000 people in the central pacific region (Fig. 1) where groundwater is a key freshwater water source (Bouchet and Sinclair, 2010). Freshwater is primarily found in the coarse alluvium aquifer along the island coastline (Fig. 6). The aquifer is small and thin and salinity levels vary throughout the year, from fresh to brackish, depending on rainfall and

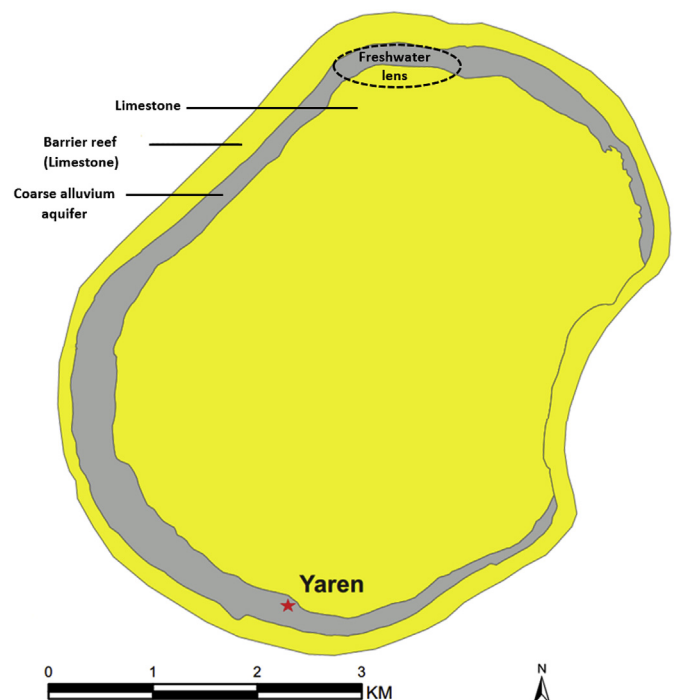


Fig. 6. Geological map of Nauru showing the two main aquifers lithology and the location of the small freshwater lens. Modified from IGRAC (2017b).

extraction. Only a small area in the northeast of the island contains a permanent freshwater lens (Alberti et al., 2017). Groundwater is used in conjunction with rainwater and desalinated water. Around half of the island's population has direct access to groundwater through privately owned wells and households with reticulated access to groundwater tend to use it for up to 83% of their water needs (Bouchet and Sinclair, 2010). Reliance on groundwater varies from about 25% to more than 50% of total water use, depending on the availability of rainwater (Bouchet and Sinclair, 2010; Bouchet, 2011). Groundwater is thus a vital source of water for Nauru and its use has been steadily increasing in the past 50 years (Bouchet and Sinclair, 2010).

Groundwater quality on Nauru has been gradually declining, despite ongoing commitment from government and donor partners to improve groundwater management. There is widespread faecal contamination from poorly designed sanitation systems, point-source contamination such as hydrocarbons, and high variability in salinity levels (Bouchet and Sinclair, 2010). High levels of pollution restrict human use of groundwater and poor groundwater quality can pose serious health risks to the community, notably for infants who are at high risk from waterborne diseases (Bouchet and Sinclair, 2010). Efforts by governments and donor partners to improve the management of groundwater have focused on technical solutions and top-down regulation. Hydrogeological investigations have focused on finding contamination-free groundwater for extraction (Jacobson and Hill, 1988; Jacobson, 1997; Castelletti et al., 2012; Alberti et al., 2017). The lack of success in this area resulted in termination of groundwater research and groundwater monitoring in 2014. Donor projects have also started trialling sanitation technologies (e.g. compost toilets, dual chamber septic tanks) for private households, however, after eight years only a dozen of these have been installed and there is no ongoing monitoring of their efficiency. Groundwater management and protection measures (i.e. identification and remediation of groundwater pollution, development of sustainable yields, pumping regulation) were included as part of the water policy developed in 2012 (RON, 2011) but it has yet to lead to any legislation or management/protection procedures. Very little has been achieved on the ground and groundwater quality is still degrading.

Failure to manage and protect groundwater is linked to the state-centred, top-down, command and control management style which prevails in Nauru. The command and control approach to regulation, through the inclusion of groundwater protection measures in the water and sanitation policy is not compatible with local practices such as customary land and groundwater ownership. Land ownership is of high importance in Nauru, and the state does not interfere with private lands. Governments are thus reticent to introduce any bill or measure that will impose regulations on private land and even though policy documents might be developed, they are unlikely to be implemented. Second, command and control management is perpetuating a mechanistic approach to groundwater studies. This has led groundwater activities to be divided between hydrogeological investigations, small scale sanitation technology trials and policy development, with little coordination or common shared vision between activities. Most activities are led by donors who have limited leverage to make sustainable change at institutional levels and limited time and budget to implement sustainable management activities.

The groundwater system of Nauru as a SES comprises human actors that rely on the resource for daily water supply, drought relief and GDEs. This complex system is affected by drivers at higher scales such as environmental changes brought by climate change. Change in water quality due to anthropogenic activities has impacted local communities to the point where groundwater is called 'brackish water' and regarded as a 'dirty' source of water (Bouchet, 2011). Even though it is widely used, low groundwater quality has created a reinforcing feedback where groundwater is poorly valued and whose protection is of low priority. Although the need to manage groundwater in a holistic way has been recognised in Nauru for more than a decade (SOPAC, 2007),

there has not been any significant improvement in either the management structure, legal framework for groundwater management, or groundwater quality and availability to date (Bouchet et al., 2014). There is a need to move away from command and control approaches both at institutional level, where a new form of collaborative, multi-disciplinary and participative form of governance is needed, and at the groundwater level, where solutions that recognise the complex adaptive dynamic of groundwater system should be developed.

Implementing the framework in Nauru would operationalise the three building blocks of the framework: complex adaptive systems, resilience thinking and Strategic Adaptive Management. For the complex adaptive systems building block a system conceptualisation would be derived to investigate how Nauruan ecosystems respond to changes in groundwater quality and the feedback that it has on the aquifer and the system slow variables. Combined with existing hydrogeological knowledge and numerical models, the system conceptualisation will allow understanding how the aquifer (including areas of potential future development) respond to combinations of various rates and methods of extraction, rainfall and temperature regimes, sea level rise and land use changes and surface activities. For the resilience thinking building block, a resilience analysis would investigate the magnitude of disturbance that slow variables can absorb before the SES reorganises and ecosystem service provision changes. It will allow developing dynamic sustainable yields of extraction, and context specific design for wells and on-site sanitation systems. With a significant increase in average rainfall forecast for years to come, the brackish aquifer could experience an ecological shift, from brackish to fresh. Understanding social TPCs for the use of groundwater will allow for both sustainable management of the groundwater resources and informed future water management planning. For the SAM building block, a SAM approach would be designed to allow improved management structures for groundwater resources, the identification and implementation of important objectives and the identification and implementation of effective technological, ecological and social management measures. The management structures will be based on a long term shared vision between groundwater users, community groups, government institutions and with the long-term support of donor partners and external supporting organisations. Hierarchical objectives will be informed by the resilience analysis and decided through the management structures. Effective management measures, based on SAM objectives, TPCs and dynamic sustainable yield will be trailed, tested and refined to best support their intent. SAM will enable the management of the resource based on SES desirability and the conservation of ecosystem services. A well-designed SAM approach will increase the system's adaptive capacity and the ability of groundwater SES to absorb and adapt to current and future pressures.

Managing groundwater as a SES requires a paradigm shift in the way groundwater is conceptualised, studied and managed. This involves a shift away from the command and control paradigm towards multidisciplinary and participative governance. In the PSIDS, future climate and social changes will bring high uncertainty in the availability and quality of groundwater. In Nauru, although groundwater could become fresher, drought may be more extreme. In order to take advantage of potential positive change brought by climate change and be resilient to negative changes and extreme events, PSIDS communities must be adaptive and recognise the complex adaptive nature of groundwater systems. In this paper, we have detailed a framework to conceptualise, study and manage groundwater as SES. It offers a new approach to manage groundwater systems under high environmental and social uncertainty. Although this framework was developed for the PSIDS, with a special focus on the limited resources and institutional challenges that these countries faces, it may also prove relevant to other contexts where groundwater is vital and environmental and social uncertainty is high.

Declarations of interest

None.

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